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Analysis of stress state in mine shaft lining, taking into account superficial defects

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Analysis of stress state in mine shaft lining, taking into account superficial defects

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Abstract. The article presents the results of numerical modeling of mining shaft lining while taking into account defects of its surface. The simulations were carried out for 64 variants, including various widths and depths of cavities in the lining. The results of the simulation are presented as distributions of the minimal principal stress and strength factor. The analysis of the obtained results allowed to indicate characteristic places in the cross-section of lining which were exposed to tensile stress. The article also analyzed the influence of the width and depth of the defects on the occurrence of tensile stress and the increase of strength factor in the lining.

1. Introduction

Mining shafts are key excavation structures as far as their importance for deep mining plants is concerned. The state of shaft lining affects not only the safety of people working in it and the transport operations, but also the functioning of the entire mine. Factors that affect the difficulty in maintaining good condition of shaft lining, are as follows, among others:

- long lifetime of shafts,
- adverse environmental impact,
- temperature changes, including freezing of the inlet shaft lining,
- rock mass deformation.

Due to the crucial importance of shafts for the mining plant operations, Polish legislation, i.e. the Regulation of the Minister of Energy of 23rd November, 2016 on the detailed requirements for underground mining operations, requirements include testing the technical condition of the lining by a qualified senior appraiser to be conducted not less frequently than every 5 years. Such expertise should include the results of tests and assessment of the technical condition of the enclosure with specification of the scope of protection and repairs, forecasts of lining wear and conditions for further exploitation of the shaft.

The testing procedure for shaft lining is described in PN-G-04211 standard “Szyby górnicze. Obudowa betonowa. Kryteria oceny i metody badań” (“Mining shafts. Concrete lining. Evaluation criteria and test methods”). According to this standard, it is necessary to check the 4 following criteria:

- the criterion of homogeneity of concrete, whose measure is the variation coefficient of concrete strength;



- the criterion of the degree of corrosion, determined on the basis of thickness of the corroded layer;
- the criterion of tightness, which depends on the level of inflow of water to the shaft;
- the criterion of the bearing capacity of the lining expressed by the confidence coefficient of stress transfer.

In addition to the above-described and relatively detailed criteria described in the standard, a very important factor affecting the condition of the lining is represented by all kinds of defects which may be a result of:

- corrosion;
- frost;
- excessive load on the shaft;
- deformation of the rock mass;
- poor quality of concrete;
- technological mistakes made during construction.

The impact of cavities on the stability of the shaft lining is not clearly defined. Only in the case of losses due to corrosion, the Polish standard defines their permissible depth as not exceeding 20% of the thickness of the lining or 12 cm.

During a visual assessment of the condition of the lining, it is essential to identify all kinds of damage, and in the case of surface defects it is important to determine the dimensions of losses, which can be done by means of direct measurements (figure 1), estimated on the basis of a recorded image, or determined by measuring and recording devices [1, 2, 3, 4]. This task is particularly difficult in the case of shafts without an extraction vessel [5].



Figure 1. Cavities in concrete and brick shaft lining.

Determination of the size of cavities is reduced to the typically technical issues and the possibility of access to the brickwork or the use of appropriate recording and measuring equipment.

Having identified surface defects and linear damages to the shaft lining, an assessment of the impact of the scope of damage on the state of stress and, as a consequence, stability of the shaft lining has crucial significance for undertaking or abandoning any type of corrective actions. Such an assessment is relatively difficult to perform and should be carried out taking into account information about the geological structure of the rock mass, material properties (particularly strength) of both the rock mass and the material of the lining, rock mass watering, its deformations caused by exploitation, as well as taking into account the current geometry of the lining, including any defects. Numerical

modeling methods [6, 7, 8, 9] can be helpful in performing such complicated analyzes, which was also included in this article.

As part of this article, a numerical analysis of the shaft lining was presented, which took into account the different sizes and shapes of cavities which damage the lining. This, in turn, allows to assess the state of stress in the damaged mining shaft lining.

2. Design of numerical models

A series of numerical simulations were carried out to investigate the correlation between the size of the cavities and the stress state of the lining. The simulations were performed with the use of a program Phase2D based on the finite element method. The model assumed for the calculation maps a shaft lining model with 1 m thickness and a diameter of 6 m. To speed up the calculation, the model included only half of the cross-section of the shaft. A lining without cavities was assumed as the initial model, and the simulation of defects was made by modifying the initial model through the subsequent removal of its structural elements.

In total, simulations were carried out for 64 variants with increasing size of rectangular-like defects (figure 2). Surface losses were simulated by removing structural elements from the model in regions whose width varied from 20 cm to 3 m (figure 3). Each variant also differed by depth of simulated defects, which was in the range from 10 to 90 cm. While generating cavities for each variant, 2 regions in the middle part of the model were removed first from layer 1 (figure 3a), and then, in the subsequent stages, the defect was symmetrically widened by another 40 cm until reaching the width of 3 m (figures 3b and 3c). The next series of variants also began with the removal of 4 elements in the middle section (figure 3d) (2 elements in 2 layers). Subsequent variants were generated again by widening this loss.

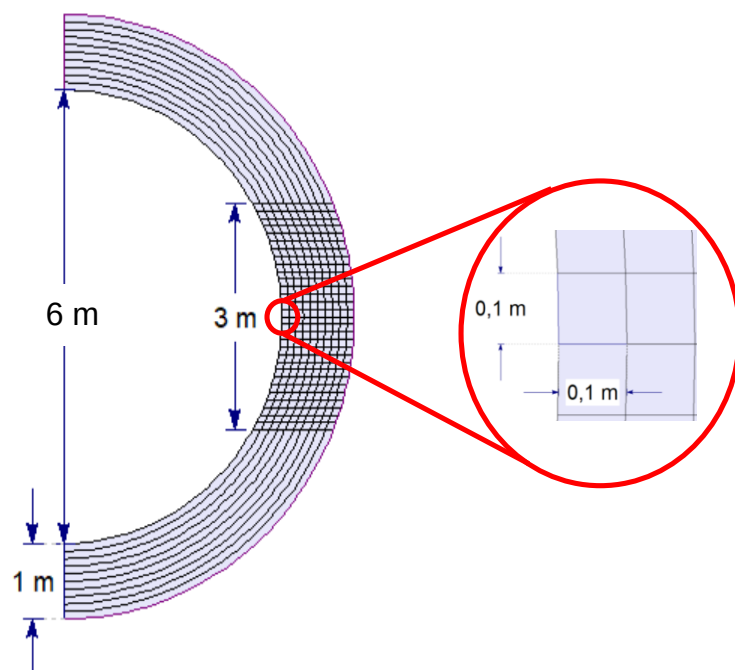


Figure 2. Geometrical model used for calculation.

Numerical simulations were carried out, taking into account the flat state of deformation. The model introduced displacement boundary conditions preventing the horizontal nodes on the side walls of the model from moving laterally, and the nodes located in the symmetry axis of the model from moving in the vertical direction. Apart from the condition of the lining, size and direction of its load has primary significance in determination of the shaft stability. The rock mass pressure is defined as a

continuous load applied in the direction perpendicular to the surface of the lining with the value of 1 MN per 1 metre of the length of its external contour.

At the first stage, the calculations were performed for the elastic model characterized by Young's modulus of 30 GPa and Poisson's ratio equal to 0.2, and the following strength parameters were adopted to determine the effort ratio: cohesion 4 MPa, tensile strength 1 MPa, friction angle 45° .

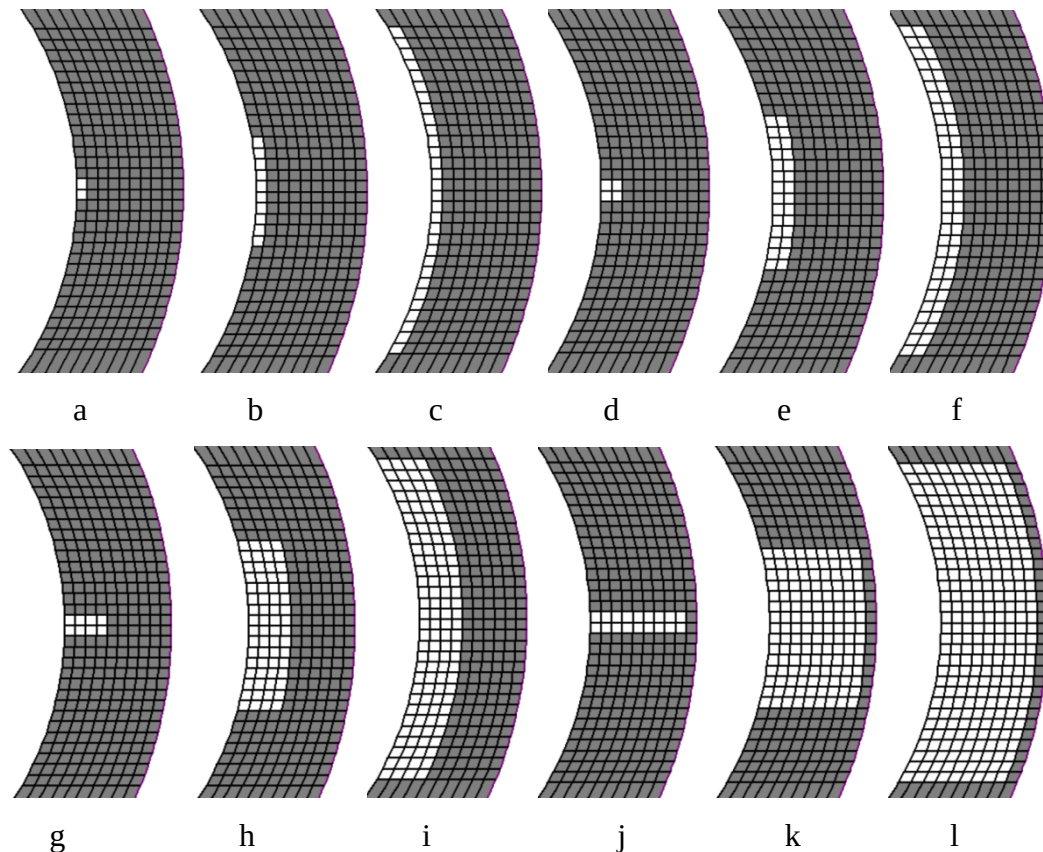


Figure 3. Chosen variants of modeled cavities.

3. Results of simulations

3.1. Tensile stress

Having accepted the above assumptions, the results were obtained in the form of a distribution of the main stresses and the strength factor, which are shown in figures 4 and 10.

The results showing the stresses are presented in the convention assuming the assignment of negative tensile stresses, i.e. the minimal principal stress (σ_3), if they take negative values, they indicate the occurrence of the maximum tensile stress.

In case of the initial model (without cavities), due to its load symmetry, there are no tensile stresses in the lining and the maximum compression occurs on the inner contour of the lining, amounting to 4.57 MPa (figure 4).

After generating voids, the model shows compressive stress concentrations and tensile stresses. The strength factor decreases when compared to the initial model. Presence of tensile stresses in the lining, which is usually made of concrete or masonry, is an essential factor of its stability. If the tensile strength in the lining is exceeded, the result is formation of cracks. The values of the minimal principal stress for selected variants are presented in figure 5.

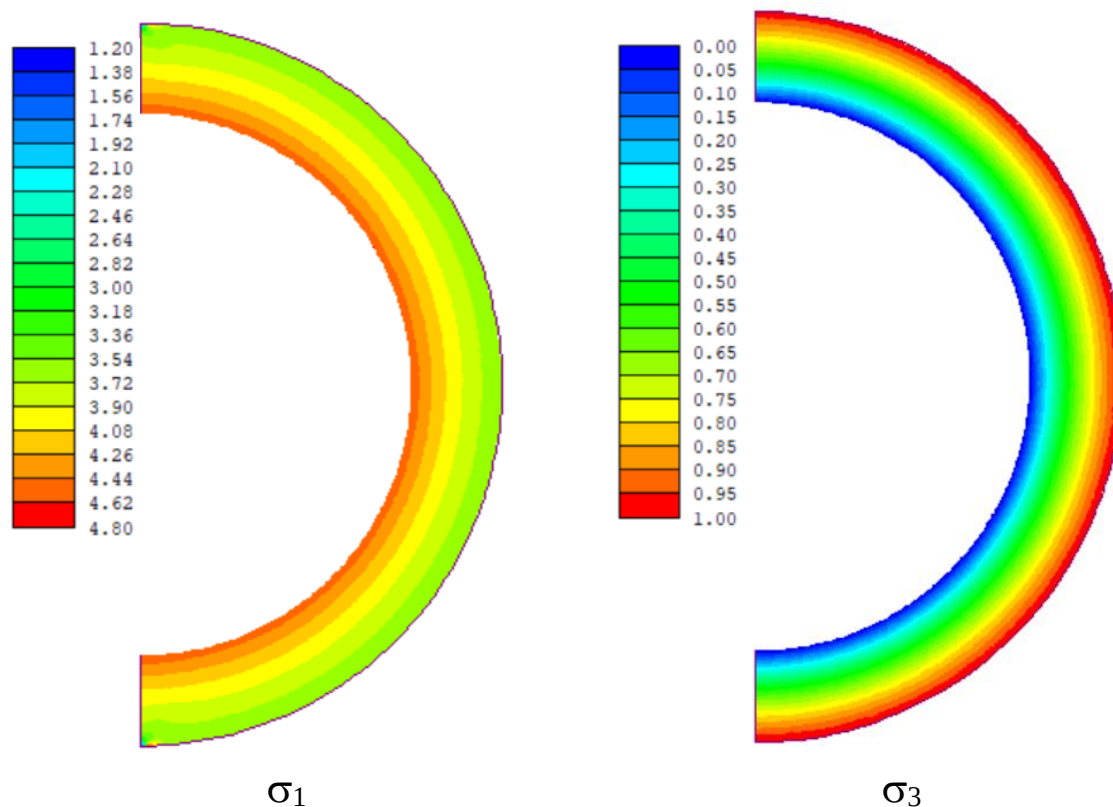


Figure 4. Stress state in shaft lining without cavities.

Tensile stresses of different intensity are generated in three characteristic places of the cross-section, depending on the width and depth of defects in the lining. In the variants where the depth of the defect is up to 30% of the thickness of the lining, tensile stresses occurred near the edge of the cavities, reaching relatively small values, maximally around 0.7 MPa (figure 5a-f).

In the variants in which the depth of defect exceeded 30% of the thickness of the lining, tensile stresses were generated on the external contour and the intensity of them depended on the depth and width of the defects. In the performed simulations, tensile stresses on the external contour occurred at a depth of at least 0.4 m and up to a maximum width which did not exceed 18 cm (figure 5g, 5h, 5j). At larger widths of the defects, regardless of their depth, the values of minimal principal stresses were positive and close to the value of applied load (1 MPa). The maximum values of tensile stresses recorded for that area amounted to 23 MPa for a cavity depth of 0.8 m and a width of 0.2 m. Such a tensile stress value significantly exceeds the tensile strength of concrete, which, in a real object, may result in a rupture of the lining from the adjacent rock mass. The relationship between the size of the loss and the quantities obtained in the tensile stress model on the outer contour of the lining is shown in a detailed manner in figure 6.

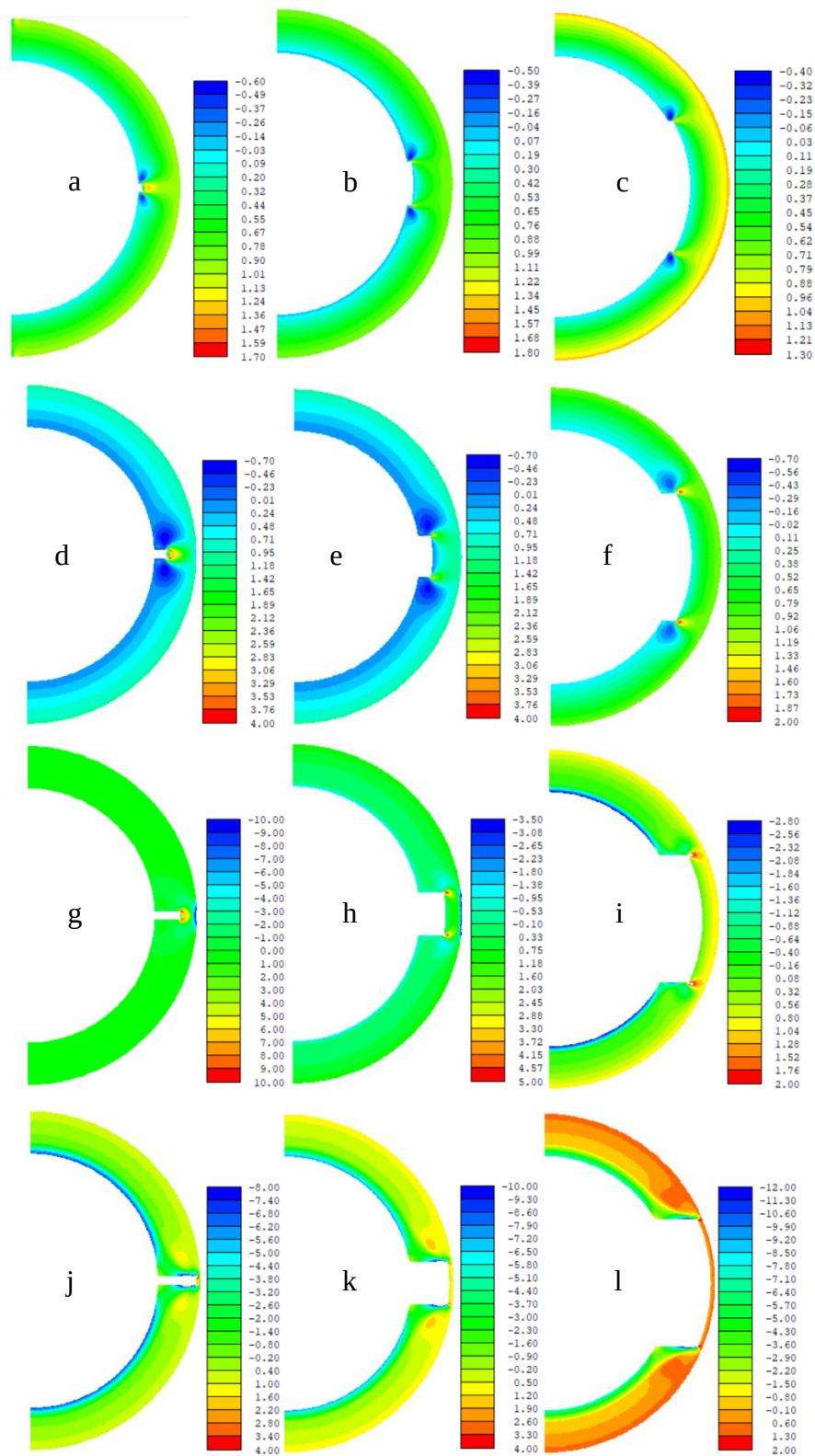


Figure 5. Minimal principal stress for chosen variants.

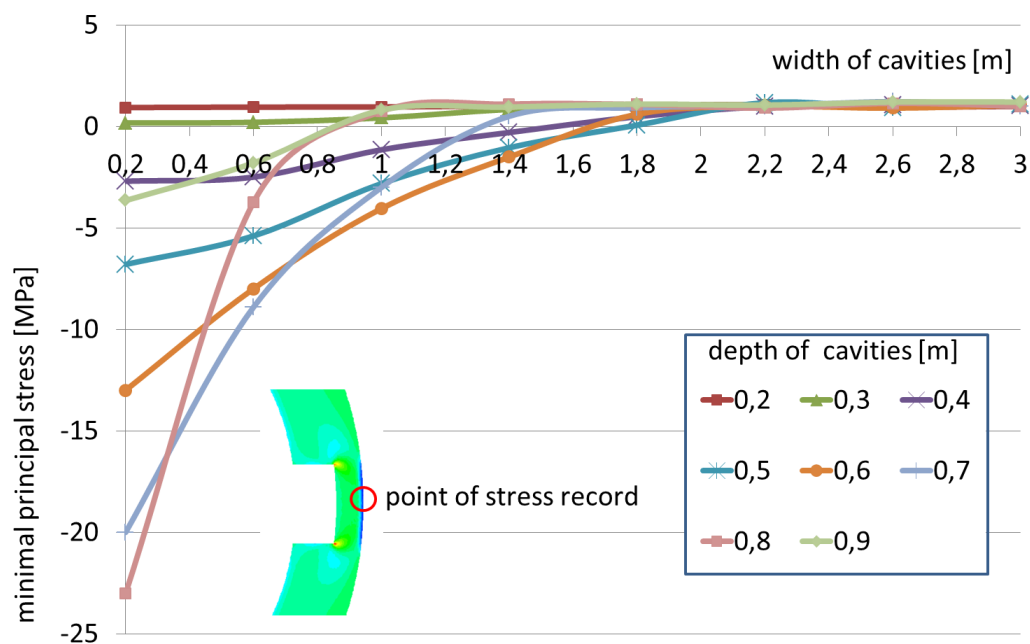


Figure 6. Minimal principal stress on the outer contour of shaft lining.

In the case of damage with a depth exceeding 50% of the thickness of the lining, tensile stresses are generated on the inner contour (figure 5h-1), with their maximum value of 8 MPa, which was obtained for the deepest defect (figure 5l). If tensile stresses occur in this place with a value exceeding the strength, the lining is subject to vertical cracking, which can be observed during inspection of shafts (figure 7). Changes in the value of the minimal principal stress on the internal contour of the lining are shown in figure 8.



Figure 7. Example of vertical crack in concrete shaft liner.

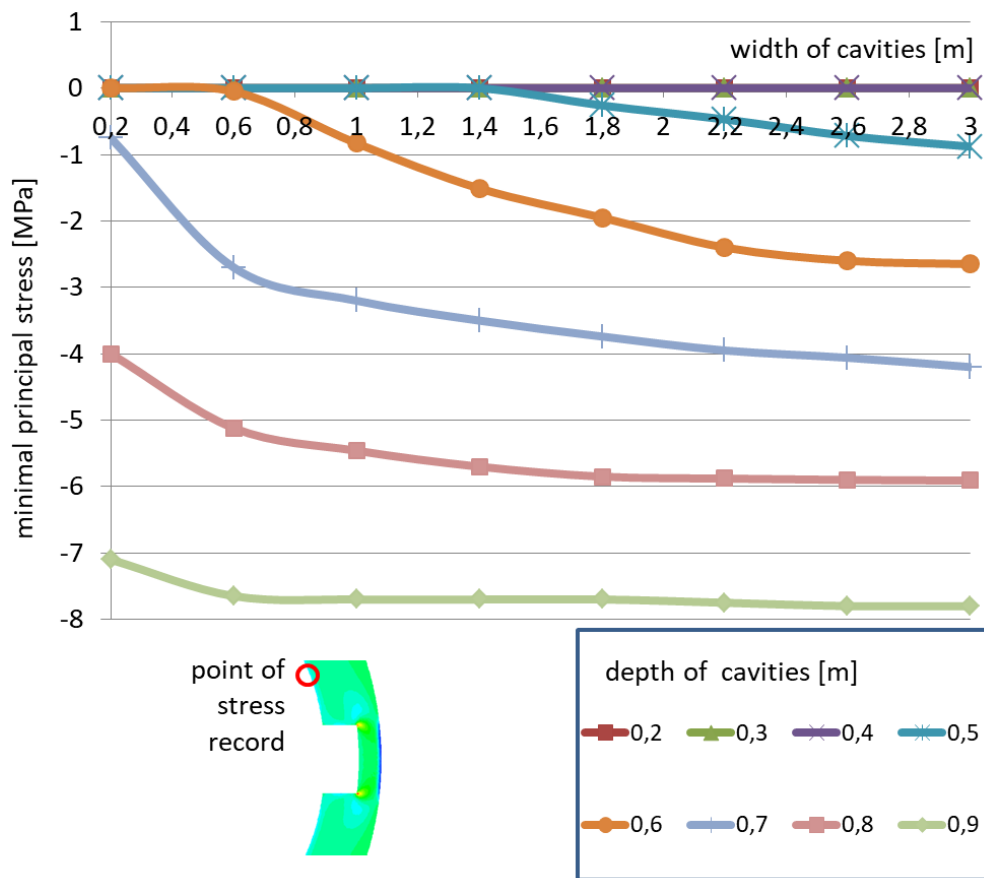


Figure 8. Minimal principal stress on the inner contour of shaft lining.

3.2. Strength factor

Apart from tensile stresses, a complex stress state may be a decisive factor that causes destruction of the structural material of the shaft (concrete or masonry). After taking into consideration the strength parameters, it may be presented in the form of the strength factor (SF) determined for the Coulomb-Mohr condition. The strength factor (SF) was determined according to the relation (1), which is graphically presented in figure 9:

$$SF = \frac{S_{max}}{S} \quad (1)$$

where:

S – actual state of stress,

S_{max} – state of stress on the failure envelope.

The value of the strength factor is determined by the stress state in the model and the accepted strength parameters, as well as the selection of the appropriate strength condition [10]. The higher the value of the strength factor, the safer the stress condition. The limit value of the strength factor is 1, for this state the stress is at its threshold. A value of the strength factor below 1 means that the stress state in the analyzed point exceeds the strength of the material, and the actual material is destroyed by shearing or crushing.

In a lining with the original dimensions, with the above-described assumptions regarding the geometry, boundary conditions and material properties, the minimum value of the strength factor occurs on the inner contour of the lining and amounts to 2.12 (figure 10).

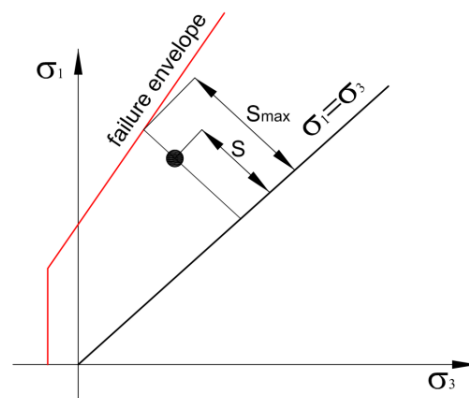


Figure 9. Graphical presentation the way of strength factor's calculation.

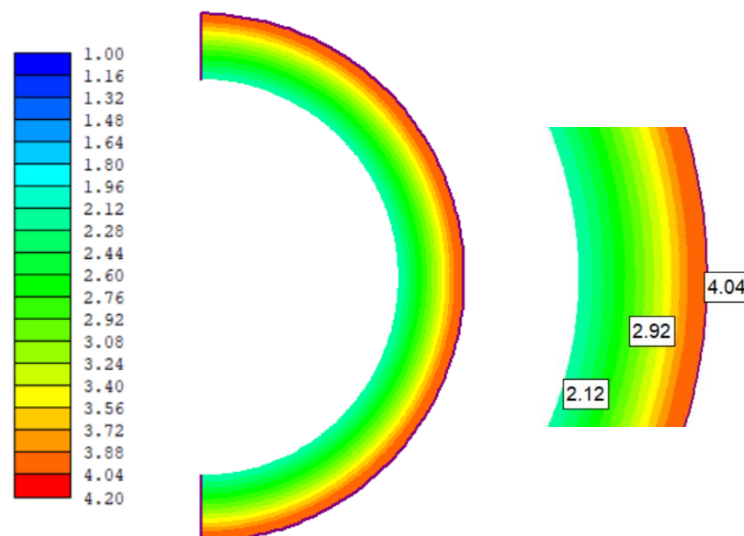


Figure 10. Strength factor in shaft lining without cavities.

Redistribution of the originally determined stress state occurs as a result of cavity modeling and the strength factor is reduced. Inside the modeled cavity, the outer wall of the lining is the place with the lowest strength factor (not including tensile stresses exceeding the tensile strength). At larger depths of defects, at tensile stresses exceeding the tensile strength of the housing material, the strength factor becomes negative.

The minimum values of the strength factor are mainly influenced by the depth of the cavity, which is presented in figure 11 for a void with a width of 1 m.

The increase in the width of the defect causes a slight increase in the value of the strength factor, e.g. for a cavity with 0.4 m of depth and 0.2 m of width, a stability index of 0.95 was obtained, whereas after increasing the width of the defect to 3 m, the stability index changed to 1.26.

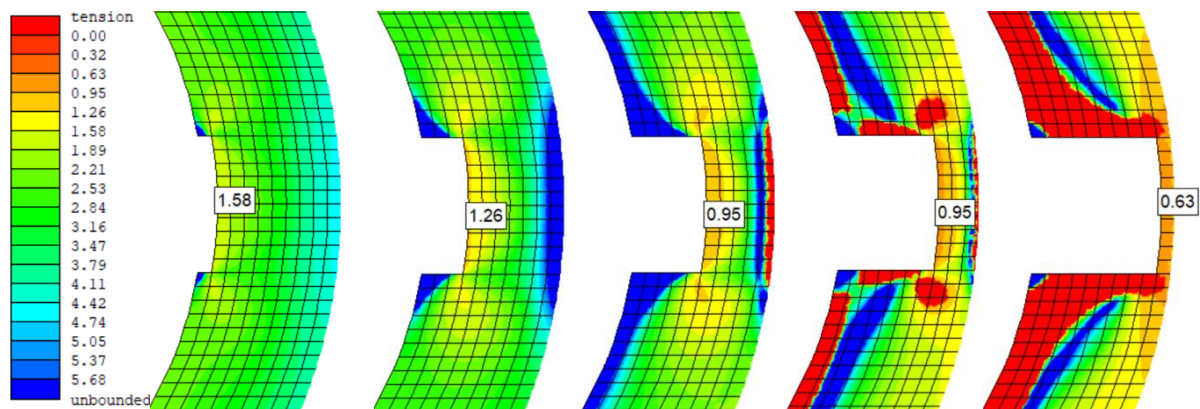


Figure 11. Distribution of strength factors for different depth of cavities.

4. Conclusion

The obtained results of numerical simulations indicate in a qualitative manner zones in the cross-section of the lining in which it is possible to experience unfavorable stress states. Presence of tensile stresses is particularly dangerous in terms of stability of the structure. However, this is not taken into account at the design stage of producing shafts (if the load around the entire circumference of the shaft is balanced and with constant thickness of the lining, only compressive stresses occur).

Taking into account both the tensile stresses and the strength factor, the obtained results indicate that the main factor that should be assessed when analyzing cavities in the lining is their depth. The numerical simulations show that tensile stresses are generated on the outer contour of the model at 40% thickness of the damage in the lining (figure 6), and on the inner contour at 50% thickness of the damage in the lining (figure 7). The occurrence of tensile stresses may result in the formation of cracks and, consequently, progressive destruction of the lining.

The results analyzed in the article were obtained on the basis of simulations carried out for a flat elastic model. Although this is a kind of simplification of the real behavior of the structure, that information allows to conclude about the possibility of damage to the shaft lining, which may be helpful in their periodic inspections and making decisions about possible repair activities.

5. References

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